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# Research Department Report

# FINAL REPORT OF RACE PROJECT 1036:

## WTDM Broadband Customer Premises Network

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# FINAL REPORT OF *RACE* PROJECT 1036:
# WTDM Broadband Customer Premises Network

**A. Oliphant (BBC), C.D. Mathers (BBC) and other Project Partners**

## Summary by BBC

*Discussions in 1985 with BBC Television showed that signal routeing in broadcasting centres presented two problems which would become more severe in the future: first, the increasing requirement for all sources to be available at all destinations, and second, the impending proliferation of signal standards (e.g. digital component signals, HDTV). The solution proposed by Research Department was the use of both wavelength and time division multiplexing (WTDM) over an optical fibre network; this inherently distributes all signals to all destinations, and with suitable terminal equipment can carry any signal format.*

*To develop the required optical and electronic technology, a consortium of European firms was set up; at just this time, the EC launched its RACE initiative; after some negotiation, the work was accepted as Project R2001, and carried out with EC support.*

## INTRODUCTION BY BBC

During the early 1980s, it became increasingly evident that the programme routeing technology employed in broadcasting centres such as BBC Television Centre had only a limited potential for future expansion and development. There were several reasons why this was so; first, new signal standards such as digital formats (e.g. CCITT Rec. 656) and future developments such as HDTV would have to be routed; second, there was an increasing demand that every source should be available at every destination; both requirements pointed towards a new kind of signal routeing system.

Discussions in 1985 between BBC Television and BBC Engineering Research Department led to the idea of combining optical wavelength-division multiplexing with electrical time-division multiplexing to form the basis of a new kind of router which promised to fulfil all of the specified requirements[1].

The BBC does not have the resources to develop the kind of technology required for such a system, and the first steps were therefore taken to form a consortium of European companies who together would be able to develop the hardware and software needed. At about this time, the European Commission launched its RACE initiative (R&D in Advanced Communications Technologies in Europe), the purpose of which was to encourage and partially fund European collaborative research projects. After some negotiations, the proposed work was accepted as RACE Project R1036: WTDM (wavelength and time division multiplexing). The leading '1' in the project number indicates that it is part of Phase I of the RACE Programme. The project, which was led by BBC Research Department, began in 1988, and was successfully completed with a working demonstration at Kingswood Warren in November 1992.

The remainder of this Report is the text of the final report of the RACE 1036 Project in exactly the form that it was submitted to RACE Central Office; it consists of contributions from all Partners including the BBC, and conforms to RACE rather than BBC format and style.

Phase II of the RACE Programme was initiated in 1993, and a new project, R2001, also managed by BBC Research Department, was set up to help WTDM technology to reach the market place. The aim is to install a pilot system in a working environment to show that the technology is commercially viable. Its projected date of completion is 1994, although this may be extended to 1995.

### REFERENCE

R.P. Marsden, J.T. Zubrzycki, J.P. Willson, 1988. Digital television routeing systems: a survey of optical and electrical techniques. *BBC Research Department Report No. 1988/3*

# RACE PROJECT 1036

# WTDM BROADBAND CUSTOMER PREMISES NETWORK

# FINAL REPORT

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# RACE
# R 1036

*(Commenced January 1988)*

# WTDM Broadband Customer Premises Network

## Final Report

## 1993

ALCATEL STANDARD ELECTRICA, S.A.
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BBC RESEARCH DEPARTMENT
KINGSWOOD WARREN

18 February 1993 36/BBC/ERD/MR/C/247/a1

# RACE PROJECT 1036

# WTDM BROADBAND CUSTOMER PREMISES NETWORK

# FINAL REPORT

## 1.0 SUMMARY

The aim of this Project has been to develop a Broadband Customer Premises Network (CPN) suitable for broadband service providers and for a wide range of applications in industry, commerce, education, and public services. The availability of such a broadband CPN will be essential to guarantee the large-scale use of the Integrated Broadband Communications Network (IBCN) for the video signal transmission that will ensure its viability in the early years. The broadband CPN uses a combination of wavelength-division multiplexing and electrical time-division multiplexing to give a total capacity on a single bearer of over 38 Gbit/s.

The Project was divided into Sub-projects as follows: system specification, electrical multiplex, laser transmitters, optical star coupler, optical demultiplexer, optical receiver, IBCN interface, control, and system test bed.

During 1988 — the first year — a detailed Technical Specification of the system and a detailed specification of testing methods were agreed by the Partners, and development work started in all Sub-projects.

During 1989, work continued on schedule in all Sub-Projects, with two important devices — the 16×16 star coupler and the fibre-coupled demultiplexer — reaching the stage where their performance could be compared with the specification. Initial tests on both devices showed good performance.

At the end of 1990, a preliminary test bed was produced in the form of an exhibit suitable for demonstrating the work of the Project at exhibitions. This exhibit showed the complete optical path from laser transmitters to optical receivers carrying digital video signals at 155 Mbit/s.

During 1991, a transmitter and receiver operating at 2.5 Gbit/s were added to the test bed, and the control system was integrated. Work continued on building the additional components needed for the final test bed. Meanwhile, a RACE II Project, R2001, was formed to specify and cost a pilot installation of a WTDM system at the BBC's studio centre in Cardiff; if the specification and cost are acceptable to BBC Wales, R2001 will go on to install the pilot network.

During 1992, the final year, the test bed as originally proposed was completed and demonstrated. A central 16×16 optical star coupler receives and redistributes fourteen wavelengths, each carrying data at 2.5 Gbit/s. Three local routeing centres generate STM-16 multiplexed data, each at one optical wavelength, and each can receive and demultiplex STM-16 data at any wavelength. Eleven of the thirteen remaining wavelengths are populated with pseudo-random data at 2.5 Gbit/s to show that no optical crosstalk problems are expected in a fully-populated system. The control software and hardware provide for any source to be selected at any destination.

The final test bed thus validated all aspects — electrical, optical, and control — of the original specification, bringing the Project to a successful conclusion and demonstrating the Partners' world leadership in broadband optical network technology.

## 2 PROJECT OBJECTIVES

The aim of this Project has been to develop a Broadband Customer Premises Network (CPN) suitable for broadband service providers and for a wide range of applications in industry, commerce, education, and public services. The work has concentrated on systems aspects, and has also included development of the enabling technology in cases where suitable devices have not been available.

The broadband CPN is based on a number of local routing centres (LRCs), each serving several sources and destinations, as shown in Fig. 1.

Fig. 2 shows a typical signal path through the system. The signals from the sources are time-multiplexed electrically at the LRC to form a serial bitstream with a gross bit rate of up to about 2.5 Gbits/s (payload about 2.4 Gbit/s). The electrical multiplexing follows CCITT Recommendations G. 707, 708, and 709 (the synchronous digital hierarchy — SDH).

The 2.5 Gbit/s serial signal modulates a distributed feedback (DFB) laser. A different wavelength is used at each LRC, the wavelengths being equally spaced 4 nm apart from 1500 nm to 1560 nm. The outputs of all the LRCs are taken by single-mode optical fibre to an optical star coupler to give a wavelength-multiplexed optical signal. The optical signals are then distributed, again using single-mode fibre, to each of the LRCs where they are demultiplexed optically and electrically to provide access at each of the destinations to signals from any of the sources in the system.

Control software allows selection of any source at any destination without centralised switching. This software controls the network, enabling it to perform all the functions required. For each specific application extra user control software will be needed to translate the customer's control procedures into the commands required by the network control.

Such a CPN provides the high capacity that is needed for communication within the customer premises in areas where video signals are handled. There is also a need for exchange of a small proportion of the internal CPN traffic with the public IBC network. One or more of the LRCs can form an IBCN interface to fulfil this function, following CCITT Recommendations as far as they have been agreed. This interface can include exchange of signalling between IBCN signalling channels and the broadband CPN control software.

Combining both wavelength and time-division multiplexing (WTDM) in this way has extended network capacities considerably, without stretching either technique beyond what can be demonstrated in a practical system within RACE timescales. The WTDM system uses fibre optics to the best advantage — the transmission of high-bitrate signals with little loss — and uses electronics efficiently in multiplexing, demultiplexing and data selection. It is an economic intermediate stage between existing technologies and more advanced, even higher capacity systems based on optical frequency-division multiplexing and coherent detection.

Several different configurations of the broadband CPN are possible to suit different applications. Networks can be connected in series or in parallel, either to provide more sources and destinations or to interconnect networks in different areas.

The Project completed an interim test bed at the end of the third year which demonstrated the key concepts of the system design, principally the optical components. A more heavily populated test bed has been produced during the fifth (final) year which demonstrates all aspects of the network, exercising all the critical elements of the system specification. The development of these test beds has included some environmental testing of the system and all its components.

In order to construct these system test beds, it has been necessary to specify, acquire, and in some cases develop components and control software which conform to the system specifications. This work was divided into nine Sub-projects: system specification, electrical multiplex, laser transmitter, optical coupler, optical demultiplexer, optical receiver, electrical selector matrix, IBCN interface, and control.

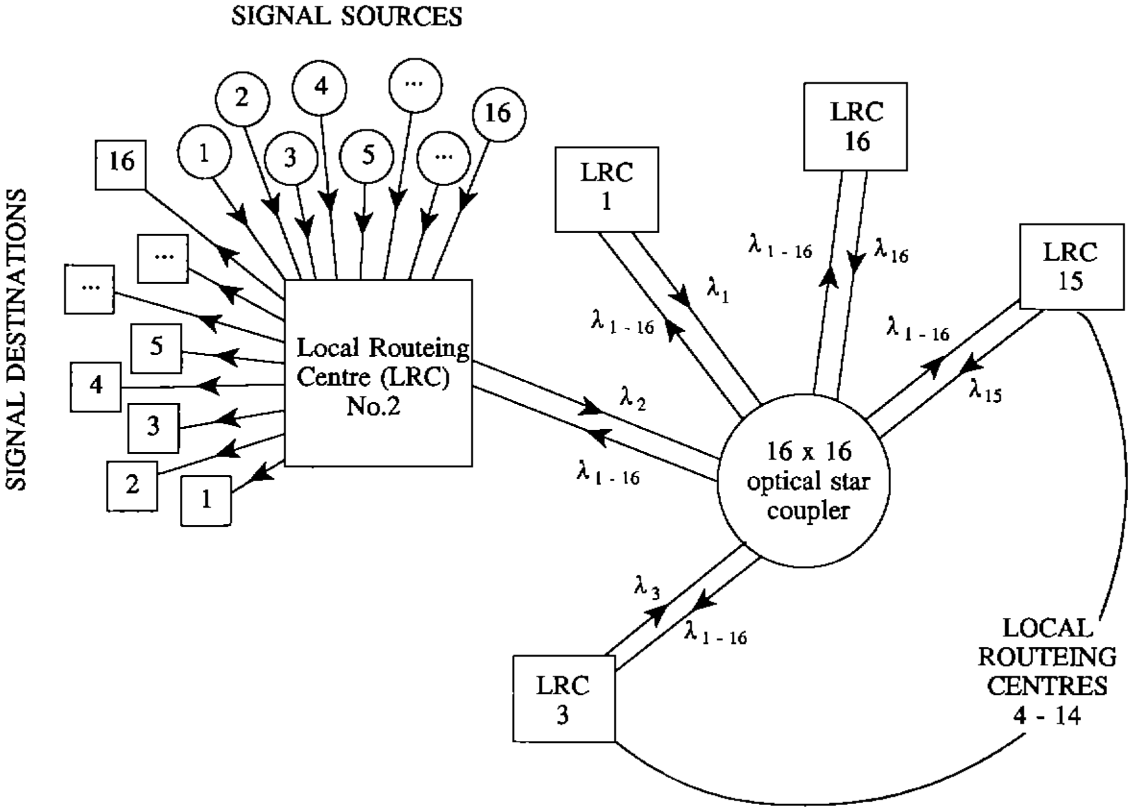

**Fig. 1.** Broadband CPN based on WTDM

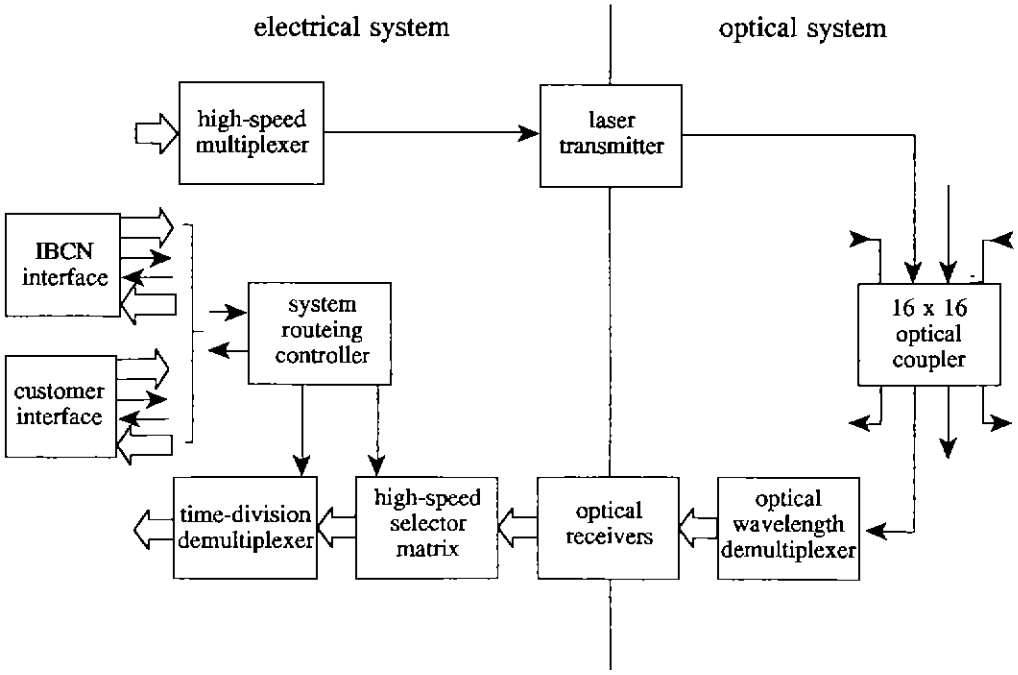

**Fig. 2.** Functional block diagram of the WTDM BCPN

## 3 RELATIONSHIP WITH THE RACE PROGRAMME

R1036 has contributed to the RACE Programme in four ways. First, it has developed a practical broadband CPN suitable for broadband service providers and a wide range of corporate applications: the video services from such a broadband CPN will create market demand for the IBCN in the early years. Second, it has developed the enabling optical and electronic technology, which should find wider application in the development of IBCN. Third, it has validated standards developed in other RACE Projects and by CCITT. Fourth, its demonstrations at international conferences and exhibitions have shown what EC collaborative projects can achieve.

The plan for the development of Common Functional Specifications has endorsed the position that R1036 has occupied in RACE. In particular, the Project has contributed to the development of IBCN in the following areas.

The Project has continued to encourage the idea that the Broadband CPN is a necessary component of the conceptual framework of RACE. The expectation that, in particular, HDTV quality will have an overriding significance in the exploitation of video is growing from some application pilots.

R1036 progress on optical components has confirmed the feasibility of implementing an increasing number of discrete wavelength channels on a single fibre. This close-spaced WDM combined with a modulation bitrate of 2.488 Gbit/s (considered high but practicable at the start of the Project) can be seen more clearly as a full exploitation of a channel when optical and electronic power levels and error performance are set. In optical matters R1036 has provided a demonstrator for technology developed in R1027 and a test bed for optical demultiplexers from R1008 and connectors from R1089.

The Project test bed in the form of an exhibit has shown that advanced components from separate RACE Projects made by companies in different European countries can be assembled into a transmission network robust enough to work reliably in an exhibition environment, thereby validating and publicising the RACE programme as a whole.

The Project has also contributed to a number of the standardisation issues in RACE. Test results on components are giving a powerful indication of the total bandwidth and the wavelength spacing that can be applied to WDM. Another important issue, not addressed elsewhere in RACE, concerns the transport of video and audio signals in transmission networks; this aspect is now being undertaken as part of the R1036 contribution to R1081 (BUNI Demonstrator).

One of the wider interests raised in the Project concerns the manner in which CPNs may be interconnected in the IBCN. This is because a network of Broadband CPNs is seen as a very powerful instrument for the sharing of specialist resources. As these usage issues become substantiated so will the levels of interaction required between CPNs become clear. The Prime Contractor of R1036 is a Partner in R1077, Usage Reference Model, and has a direct interest in broadband connections via the public networks, and so is well placed to monitor these developments.

The Project has contributed as required to Concertation Meetings. As the Project had interests in both Project Line I and Project Line IV (which was chaired by the Project Manager during 1992) the Prime Contractor is grateful to GEC Hirst Research and BNR Europe Limited and to R2001 Partners GEC-Marconi Ltd who have represented the Project in Project Line I.

## 4 MAIN ACHIEVEMENTS

### 4.1 System Specification

A very detailed specification of the system, its component parts, and the interfaces between them was drawn up in the first six months of the Project. The thoroughness of this specification was validated several times during the Project when components from different Partners were assembled to tight deadlines for important demonstrations. After some initial measurements of laser wavelength, it was agreed to standardise on measurements made in air (rather than in vacuo). Measurements made by Partners finally agreed to within 0.07 nm; this is more than adequate for checking lasers whose wavelength is specified to ±0.7nm.

## 4.2 Electrical multiplex and demultiplex

The system partitioning has produced 5 custom ICs; two of these, the high-speed bit interleaver and the high speed bit deinterleaver operating at 2.5 Gbit/s, were designed in silicon by Swindon Silicon Systems and fabricated by SGS-Thomson. The remaining three operating at 155 Mbit/s were undertaken by Alcatel SESA. In all, the five chips were intended to cover the following functions (see block diagram):

(i) Bit interleaver and signal multiplexer

(ii) Bit de-interleaver and signal demultiplexer with sync detection

(iii) Channel adaptor (CHANA): to interface with terminals up to 80 m away, providing frame alignment and control data insertion.

(iv) Data shuffler and scrambler (SHUMBLER): to perform data re-ordering (so that a simple bit-interleaver at 2.5 Gb/s can perform the more complex task of octet interleaving as required by CCITT Rec. G.707) as well as the transmission scrambling and descrambling according to CCITT Rec. G.709.

(v) Data channel and Master Timing (DAMAST): with the 2 Mb/s data channel FIFO.

First versions of the high-speed multiplexer and demultiplexer were designed by SGS-Thomson Microelectronics and fabricated using the HF3C process, in the knowledge that the resulting chips might not achieve the required speed. This indeed proved to be the case, and the work was then subcontracted to Swindon Silicon Systems.

The multiplexer and demultiplexer ASICs are high-performance devices that operate at bit rates in excess of 2.5 Gbit/s. The goal was to demonstrate the design and fabrication of multi-gigabit devices on a silicon process. The advantage of using silicon technology as opposed to III-V technologies such as gallium arsenide is that the ultimate production costs will be significantly lower, thereby reducing the overall costs of high bit rate communications systems. Fabrication of such devices however is not feasible on standard production silicon processes and therefore a development high performance silicon bipolar process was chosen. The process is being developed under the Esprit TIP-Base Project and the devices are used as technology demonstrators for that Project.

Due to the high-performance nature of these devices and the status of the technology, a full custom design approach was undertaken. This required extraction of basic electrical device characteristics from the process data.

The critical design problems of the multiplexer and demultiplexer are quite different and are outlined separately:

The multiplexer device operates as a 16 to 1 multiplexer with inputs at 155.5 Mbit/s and an output driver operating at 2.5 Gbit/s. The major design issues are the production of the 2.5 Gbit/s output, and keeping the overall power consumption of the device low to allow it to be packaged in a standard 44 pin ceramic chip carrier. A suitable output stage based on a differential open-collector output driving an external transmission line was designed. The device power consumption has been maintained at 700 mW. The evaluation results of the first iteration of silicon demonstrated the devices operating in excess of the required specification (Fig. 3).

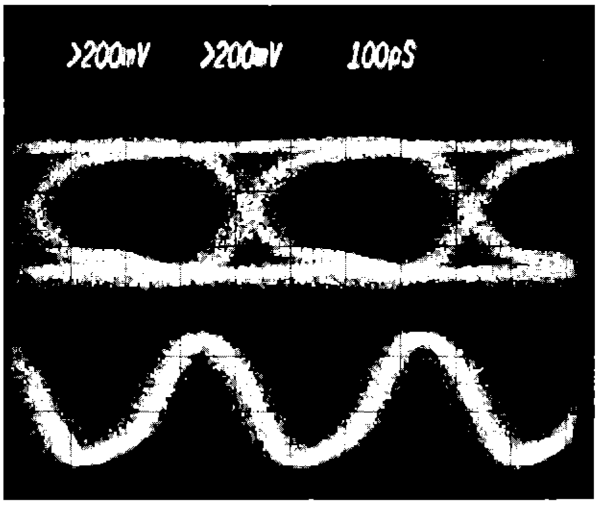

**Fig. 3.** 2.5 Gbit/s output from the multiplexer

The demultiplex device was designed to operate as a 1 to 16 demultiplexer with word-recognition circuitry to identify a pre-programmed frame word in the 2.5 Gbit/s serial bit stream. The main design task in this device is to identify the frame word in the 2.5 Gbit/s serial bit stream and to alter the output sample timing to align with the frame word. To achieve this the recognition circuit has to compare the input serial bit stream with the frame word on a bit by bit basis, thereby effectively carrying out this 16 bit word recognition within a 400 ps clock cycle. The circuit also has to operate at minimum power so that a standard 44-pin ceramic chip carrier can be utilised. To achieve this recognition function an approach was taken whereby the serial data was converted to 4 bit parallel, and processed at a lower rate. This significantly increased the complexity of the device but is optimum for the technology with respect to device power consumption. The first iteration of silicon performed well and fulfilled the specification. The multiplexer and demultiplexer cards are shown in Fig. 4.

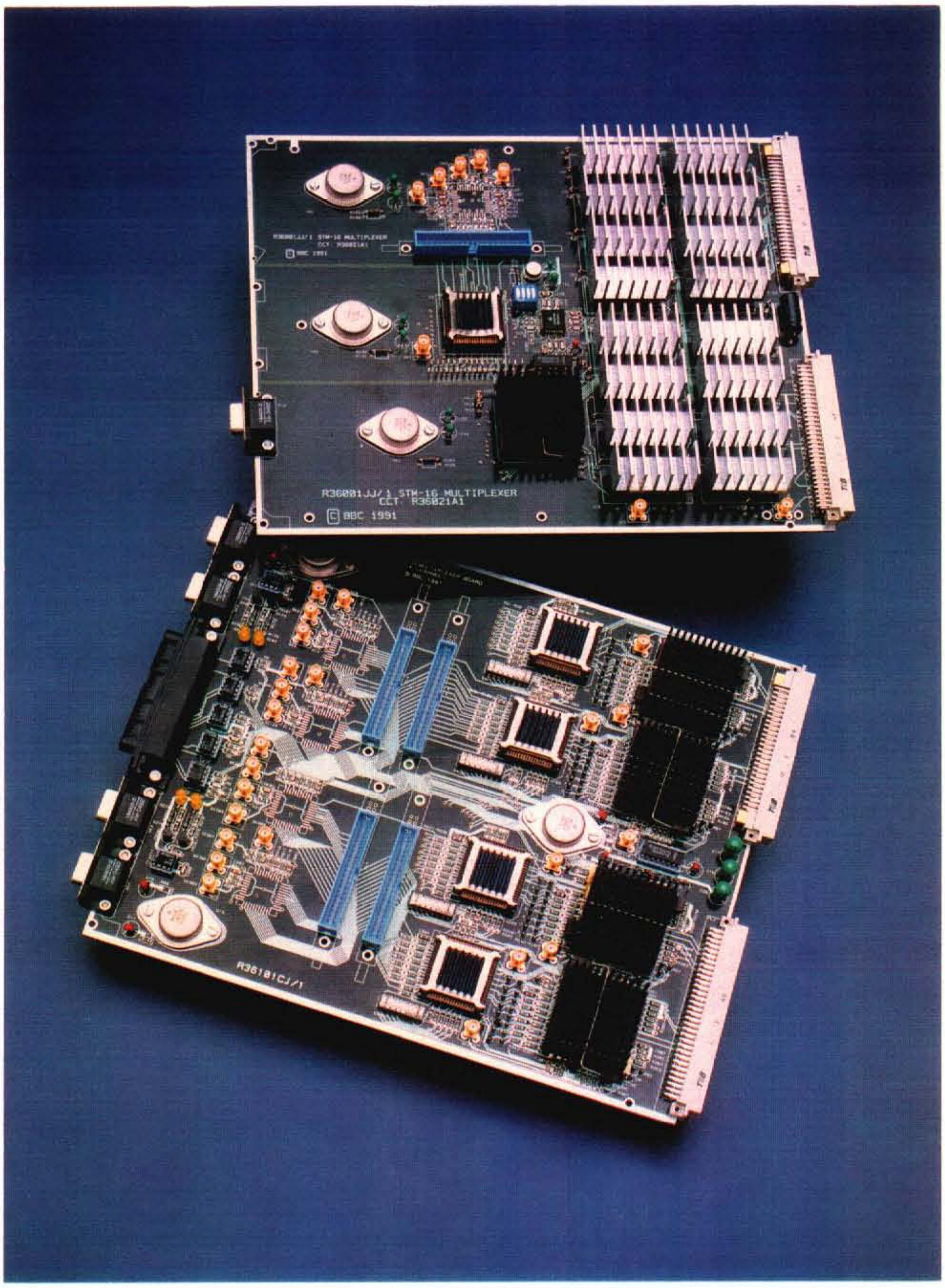

**Fig. 4.** Electrical multiplex and demultiplex cards

The three 155 Mbit/s chips designed by Alcatel SESA are as follows:

1. The Channel Adaptor ASIC has been designed and manufactured with the AT&T bipolar ECL technology (SFOXIL), and 41 working samples are available.

2. A Shuffler-Scrambler (SHUMBLER) ASIC; this full-custom IC has been designed with SGS-Thomson's 1.2 $\mu$m BICMOS technology, and processed through the Esprit 2 Project CANDI (2268). The chip has been successfully tested at the maximum allowable speed by the equipment limitation (100 MHz), however the operation of the SHUMBLER at the specified speed (155 MHz) has been marginal and unreliable showing a very poor yield at this frequency.

   Since a new redesign with other technology was not feasible within this Project, the SHUMBLER has been replaced by a daughter board, designed to implement the minimum SHUMBLER functions required by the MUX and DEMUX without fully meeting the CCITT Recommendations.

   SGS-Thomson Microelectronics are also in process of developing a version of the SHUMBLER to work with the VITESSE 8:1 multiplex/demultiplex chipset.

3. Data-channel and master timing, designed and processed with the AT&T Bipolar ECL Technology (BEST). After several processes, the samples still showed thermal instability and very poor yield. Of the two main functions of this chip, the master timing generation worked correctly, but the data channel handling function had to be disconnected in order to reduce the power dissipation of the DAMAST and guarantee the overall operation of the demonstrator.

Seven double-Eurocard size, six-layer boards have been designed and manufactured, and after considerable modifications resulting from the problems with the SHUMBLER, are fully operational for the electrical subsystems, three for the 155 Mbit/s STM-1 to 2.48 Gbit/s STM-16 multiplexer and four for the demultiplexer (four STM-1 channels per board extracted from STM-16).

### 4.3 Laser transmitters

At Northern Telecom the RACE 1036 objectives were:

- To develop a laser package capable of 2.4 Gbit/s operation, incorporating 50 Ω input impedance via an SMA connector, a thermo-electric cooler, and internal rear facet monitor diode for power control;
- To produce circuits for controlling both the laser temperature and the mean power;
- To produce a circuit capable of modulating the laser at 2.4 Gbit/s.

The laser transmitters would be assembled using single-frequency distributed-feedback laser dice, and would be required to cover the wavelength range from 1500 nm to 1560 nm with a 4 nm channel spacing. The wavelength of each laser source would be determined during manufacture of the laser chip. Fine tuning of the wavelength would be done by temperature regulation, using the internal Peltier cooler. The laser die would be optically coupled to a single-mode fibre.

The laser mean-power and temperature control circuit was designed to maintain a distributed-feedback laser submount at a set bias current and temperature, dependent on the electro-optic efficiency and wavelength of the laser respectively.

The laser control circuit was designed around standard, commercially available parts, with internal voltage reference, and uses feedback from the laser's internal monitor photodiode to maintain the laser at a constant monitor photocurrent.

The laser package internal Peltier effect heat-pump is controlled to maintain the laser die temperature to within specified limits. The original temperature control circuit used a dual power operational amplifier to control the laser package heat-pump. This circuit proved to be unstable. The modified circuit uses a precision voltage reference to control a programmable current source for the thermistor circuit. This is also used to set the reference for the submount temperature for fine tuning of the laser wavelength. The controller senses the thermistor voltage and compare this against the reference.

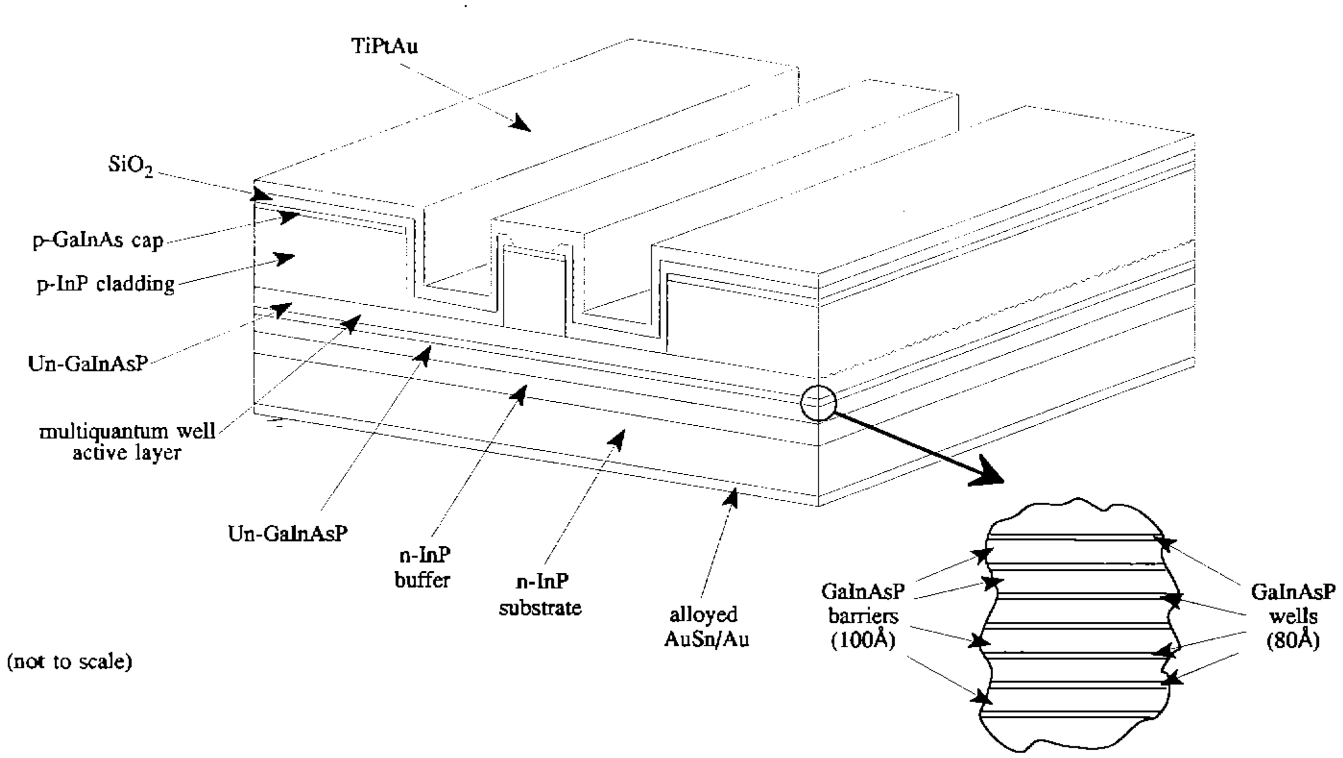

**Fig. 5.** Multiple quantum-well distributed-feedback laser

The error voltage causes the Peltier control stage to heat or cool the submount to achieve thermal stability. The precision voltage reference is also used for setting the bi-directional current limit circuit which is provisionally set to 1 A.

Power supply regulation is achieved with two voltage regulators mounted on the PCB. Both regulators, which are switched on with a key, have a slow turn-on circuit to prevent power supply transients and additionally the supplies are interlocked so that the -5 V supply does not turn on until the +5 V supply is established.

The laser control circuit features four warning alarms, LASER ON, LOW IM (laser degrade), LASER OVER TEMPERATURE and LASER UNDER TEMPERATURE. The LASER ON alarm operates when a photocurrent of greater than 0.025 mA is present whereas the LOW IM operates when the monitor photocurrent falls to 70% of its intended value. Temperature alarms are nominally set to ± 5°C of the required laser operating temperature, this corresponds to a ± 0.4 nm drift in wavelength for a typical DFB laser.

The laser modulator circuit is based on the Fujitsu laser driver GaAs IC type FMM311CG, specified for operation to 2.7 Gbit/s NRZ. The laser modulation current is AC coupled to the laser via an SMA connector and 47 Ω resistor in the laser package. A GigaBit Logic modulator IC was also evaluated but was found not to operate satisfactorily in conjunction with the mean power control circuit.

It was decided to replace the original bulk-active distributed-feedback (DFB) laser type with multiple quantum well (MQW) DFB laser dice provided by R1027 (Fig. 5). These MQW DFB devices differ from the earlier bulk-active DFB devices in that they exhibit much narrower spectra and are much less likely to exhibit TM mode peaks. These characteristics are beneficial, in terms of improving the performance of a dispersion-limited system and by improving the feasibility of a reduced channel spacing. In addition, the MQW devices have lower threshold currents and improved efficiency over bulk-active devices.

Five wafers were supplied from RACE 1027 to cover all the channels. These wafers were then cloven into bars, facet coated, chipped up and electrically tested. Quantities of laser dice from each wafer were mounted on to submounts for evaluation and spectral testing before assembly into packages. Because of the poor wavelength yield this proved to be costly in both assembly time and materials, so a new procedure was implemented. This involved pulse-testing the laser chips for wavelength under controlled conditions, and only bonding on to submounts those that met the wavelength requirement.

After testing and assessment, the good submounts were assembled into laser packages and coupled to single-mode fibres; the laser packages were then hermetically sealed. The packaged lasers were tested, given a stabilisation burn-in and then post tested. Plots of the light vs. current characteristic of each laser at 25°C, and the small-signal swept frequency responses were obtained.

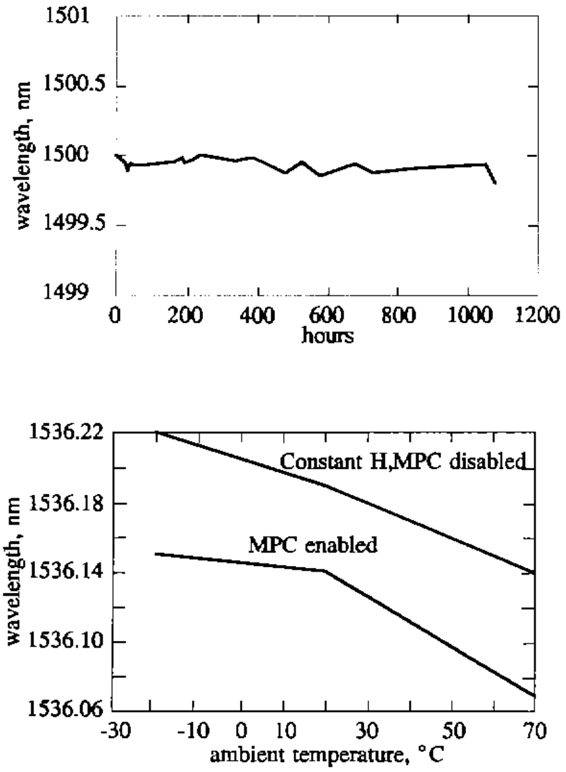

**Fig. 6.** Laser wavelength variation with time and ambient temperature

A sample of the finalised PCB assembly and laser package were put on life test for over 1000 hours at room temperature. The change in laser optical power was less than ± 0.025 dBm, and the change in wavelength less than ± 0.07 nm. The PCB/laser package assembly was cycled over temperature between -10°C and +55°C with the submount at 25°C and showed a wavelength change of only ± 0.073 nm; see Fig. 6 which shows wavelength variation with time and temperature.

The magnitude of the peak optical power is limited by two criteria — the efficiency of the laser, and the amount of modulation current available from the Fujitsu modulator IC.

The completed modules were set up for best eye-height and minimum bit-error rate using a receiver loaned by the BBC. The transmitter modules were then connected to 6 km of dispersion shifted fibre and final fine adjustments were made.

Unfortunately, because of a shortage of laser dice at 1556 nm and 1560 nm, these two channels have not been populated.

### 4.4 Star coupler

The central 16×16 star coupler for the Project test bed was produced by GEC Hirst Research using fused tapered-fibre technology, and is built up from discrete 2×2 couplers. Early work during the first six months of the Project was devoted to optimising the wavelength-independence over the required 60 nm range, and reducing the excess losses of individual 2×2 devices. In a Taguchi-method analysis programme, 250 devices were fabricated, and a great deal of knowledge was gained of the factors affecting performance. Once satisfactory performance was achieved repeatedly, an unpackaged 16×16 star coupler was built. Interim deliverables including 2×2 and 4×4 couplers were produced to demonstrate the capabilities of the fabrication process prior to the delivery of the final 16×16 star coupler.

A 16×16 coupler was packaged using a design based on modified splice organiser trays supplied by GPT/TCL (Fig. 7). The housing (380×105×95 mm) comprises eight such trays hinged together, each containing four 2×2 couplers and up to three splices. Within the package, the fibre bend radius is maintained above 4 cm to prevent unwanted bend losses. The input and output fibres were strain-relieved to allow reasonable handling of the component. The coupler was fully re-characterised

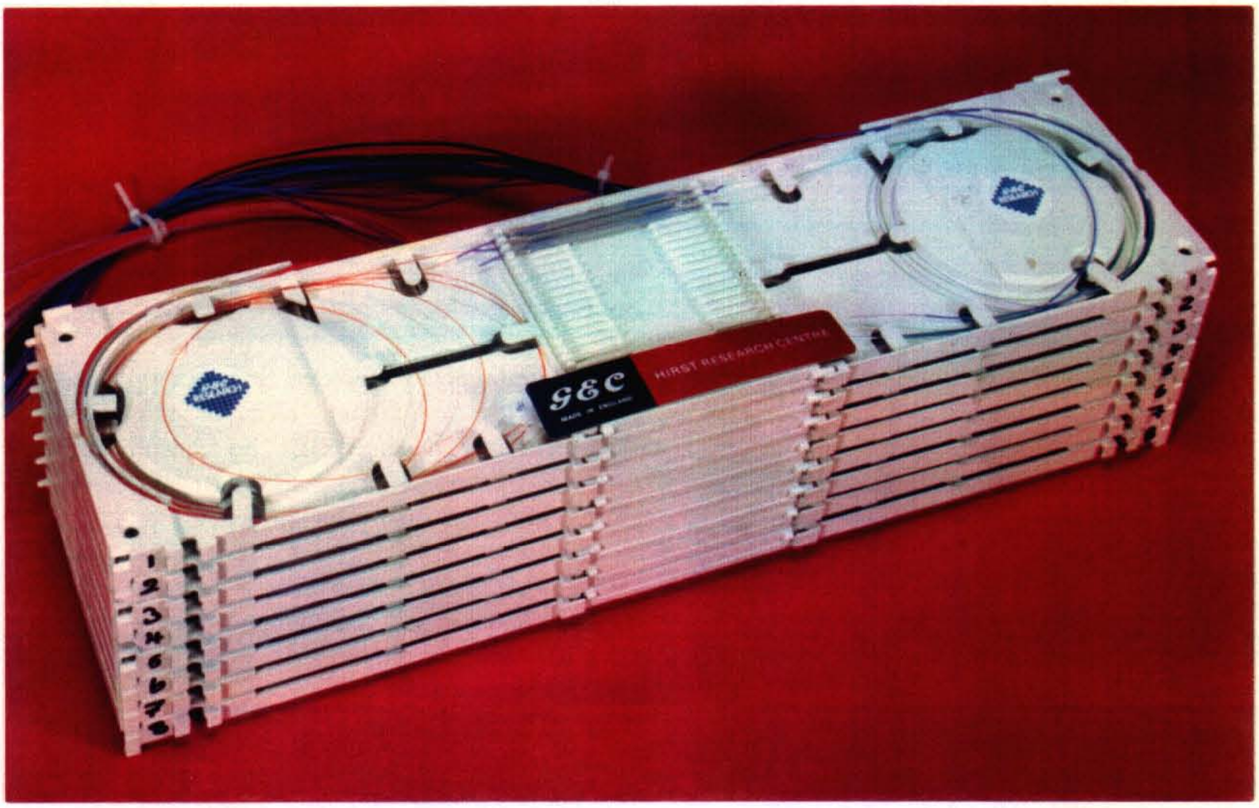

**Fig. 7.** All-fibre 16×16 star coupler

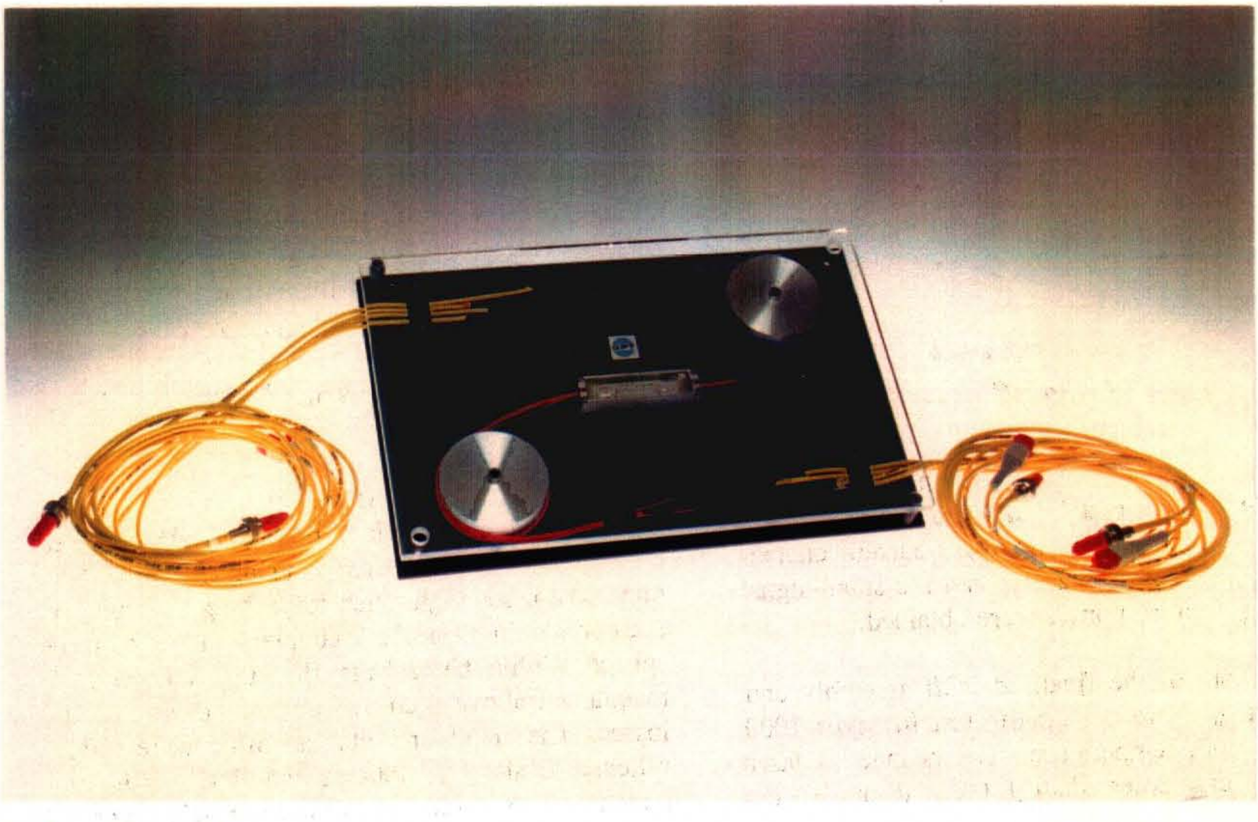

**Fig. 8.** Integrated-waveguide 4×4 star coupler

following packaging, and the 256 routes were found to have a mean loss of 13.4 dB, with a standard deviation of 0.5 dB. At the time of its fabrication, this component represented the state of the art for a 16×16 wavelength-flattened fibre star coupler, in terms of uniformity, excess loss and operating wavelength- range.

Germania-doped silica integrated optic-waveguide components were investigated as a longer-term low-cost alternative to fused-fibre technology for the star coupler. The waveguides were fabricated using microwave plasma-assisted chemical vapour deposition and reactive-ion etching. During the first two years, 2×2 and then 4×4 couplers were successfully produced. These were based on a directional coupler design which was selected to provide minimum variation (< ± 0.1 dB) of splitting ratio over the system operating band (1500-1560 nm). An additional 4×4 device, which was packaged and connectorised for use in the Project exhibit, can be seen in Fig. 8. As with the fibre-based devices, the larger star couplers were built up from an assembly of 2×2 directional couplers. A 16×16 star coupler was designed, based on the multiple 2×2 approach (Fig. 9) and a number of process runs to fabricate these devices were performed. The component parts of the 16×16 star were demonstrated to be working with performances close to their expected values, but the resources remaining in the workpackage were insufficient to allow the production of a full 16×16 coupler.

Subsequently, a new radiative design for this type of component was proposed, which significantly reduces the complexity of the component. The major advantage of this design is that its theoretical efficiency for large port counts N is independent of N. Additionally, the design is inherently wavelength-insensitive. These factors have resulted in the design receiving much attention worldwide.

As the work of BNR Europe Limited on the diode-coupled demultiplexer had been completed by December 1991, it was decided to use the remaining few man months effort to progress the development of the BNR low cost N×N integrated optic central star coupler, based on a silica-on-silicon radiative star (Fig. 10), for RACE 2001, the WTDM pilot. This decision was made with the full agreement and encouragement of RACE Central Office. This work builds on the basic silica-on-silicon technology established in RACE I Projects R1008 and R1089.

For N×N central couplers of medium to high port count (ie for N greater than 8), it has been shown that the integrated optic radiative star scores heavily over the conventional multiple 2×2 fused fibre approach in terms of flexibility, future proofing and cost.

The specific requirements of the central optical

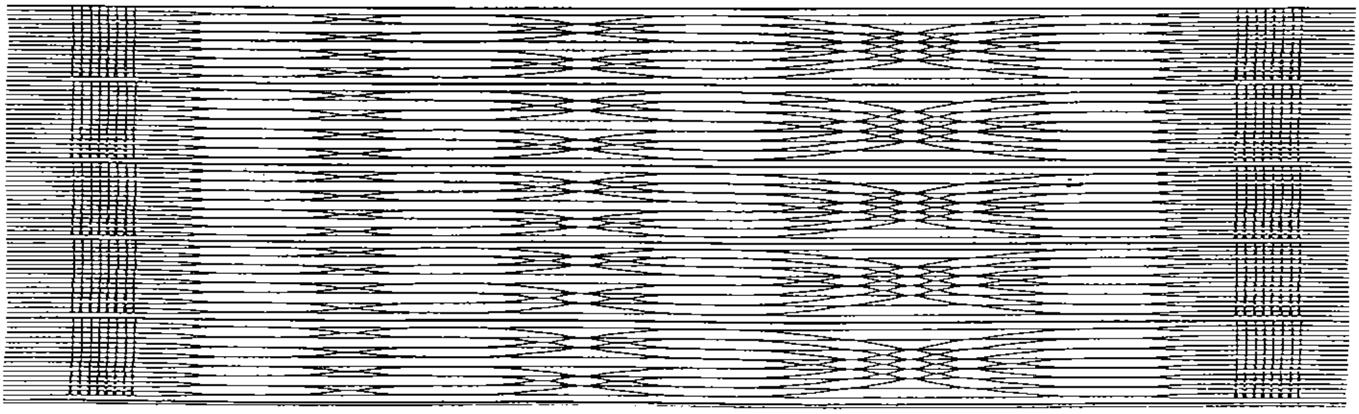

**Fig. 9.** Electron-beam mask for the 16×16 planar waveguide coupler

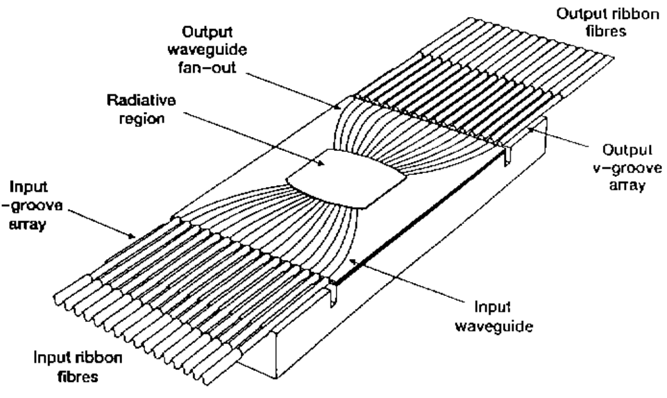

**Fig. 10.** Radiative 16×16 star coupler

couplers have been studied and compared with the expected performance of the silica-on-silicon radiative star component to be delivered in the third year (1994) of R2001.

The choice of optical architecture for the pilot installation has not yet been finalised, but it will be based on multiple N×N central stars, where N is between 8 and 16. The RACE 1036 system and the original proposal for RACE 2001 are based on 16×16 central star couplers, and so the studies in this workpackage have been concentrated on the 16×16 component. Parameters such as worst case insertion loss, port-to-port uniformity, wavelength response, polarisation response and return loss, have all been considered. A target specification has been determined for a fibre-pigtailed and packaged 16×16 prototype device for the pilot installation in 1994.

The critical issue is worst-case insertion loss, and the target for the 2001 installation has been set at 18 dB (including 12 dB splitting loss). However, computer modelling on new radiative star designs, which takes into account the expected improvements in silica-on-silicon waveguide technology and general process capability, has shown that a worst-case loss of 15.5 dB (14.7 ± 0.8 dB) should be achievable in the long term. This value compares favourably with the state of the art fused-fibre coupler technology, and the silica-on-silicon technology is a much more viable long-term commercial solution offering considerable cost benefits.

Substantial progress has been made during 1992 in RACE 2001 towards meeting the performance target for the 16×16 component for 1994 for the pilot installation and realising the longer term target of a worst case port-to-port insertion loss of 15.5 dB.

It is imperative that the approach chosen for the 2001 pilot system is readily capable of capacity and functionality enhancement or modification in order that it can be adapted to a wide range of broadband CPN applications in industry, commerce, education and public services, thus achieving economies of scale and a successful exploitation. It is concluded that the radiative star, with its inherent flexibility and future-proofing offers an attractive route for achieving that goal.

### 4.5 Optical demultiplexer

At the beginning of the Project it was decided that a fibre-coupled optical demultiplexer would be developed by Instruments S.A. Jobin-Yvon for installation in the system test beds, while a diode-coupled type would be developed by BNR Europe Limited which could be integrated with multi-channel receiver electronics, and which would find application in future projects.

Before manufacture of the fibre-coupled demultiplexer by Jobin-Yvon, a considerable amount of research work was required. First, two types of fibre array were fabricated, and comparisons made between real and nominal fibre positions; this indicated that the centre-wavelength accuracy of each channel should be better than ± 0.1 nm. Two views of the fibre array are shown in Fig. 11. Calculations were then carried out in order to obtain the best compromise between optical aberrations and sensitivity to polarisation; this is necessary because fluctuations in the polarisation of an optical path are converted into amplitude fluctuations (i.e. noise) if the demultiplexer is unduly polarisation-sensitive.

The Stimax configuration was used in two initial designs: short-focus (SFS) with a 300 gr/mm grating, and long-focus (LFS) with a 180 gr/mm grating. The SFS configuration showed the better performance and was adopted. In all respects it performed better than the Project specifications. For example, 3 dB insertion loss and 2dB polarisation loss are specified as maximum; measurements with

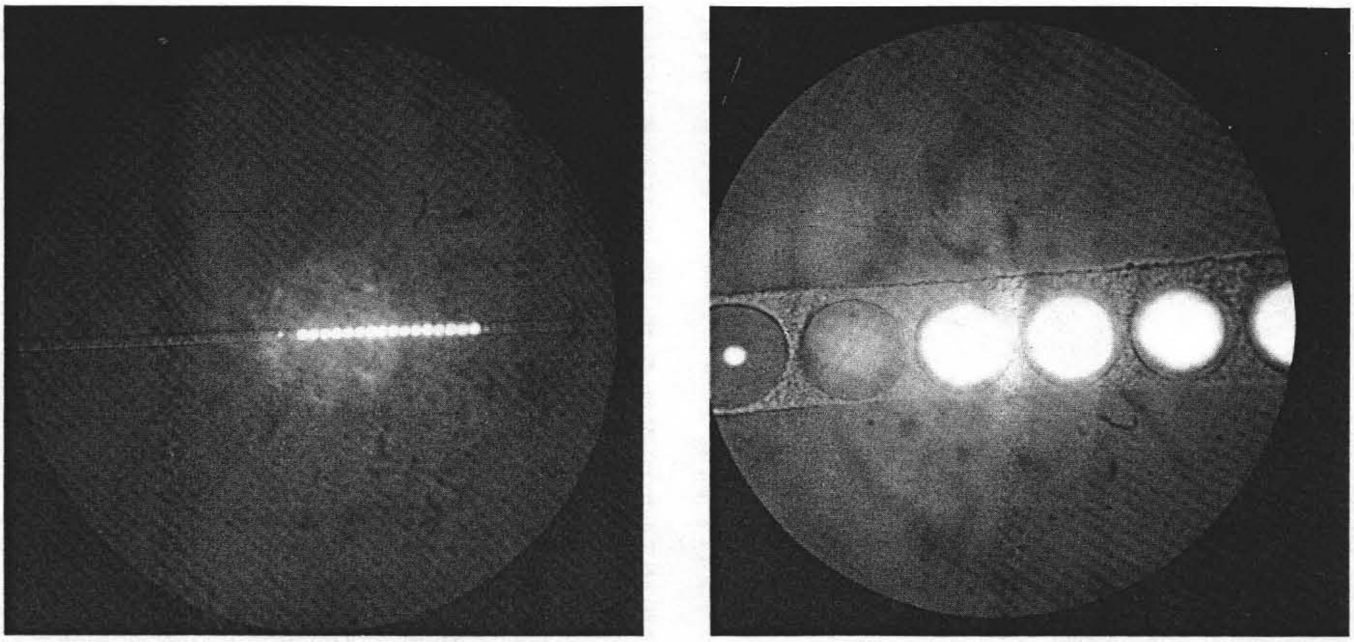

**Fig. 11.** The 16-fibre array in the fibre-coupled wavelength-demultiplexer

unpolarised light (and therefore including some polarisation loss) showed a total loss of between 1.6 and 1.9 dB, i.e. up to 3 dB better than specification.

In order to improve the demultiplexer with a view to future systems requiring more channels, wider passbands, and use with single-mode fibre outputs, two new stimax configurations were studied and compared to the first type with its spherical mirror. These used a parabolic mirror, and a plane-corrected spherical mirror, (i.e. with a block made of two materials with different refractive indices and a plane interface). The results showed that both the parabolic and the plane-corrected types produce diffraction-limited spots at the centre of the field, and a very small aberration at the field edge compared to the original spherical stimax. The plane-corrected type is easier to make since it does not involve the grinding of a parabolic mirror.

The object of the work by BNR Europe Limited in this workpackage has been to design and develop a novel demultiplexer in which a photodiode array replaces the conventional array of output fibres. This approach offers considerable potential benefits in cost and compactness and is a necessary stepping stone to the longer term goal, not within this current programme, of a demultiplexer incorporating an integrated receiver.

A good understanding was first gained of the design criteria for the diode-coupled demultiplexer and in particular the detector array constraints were determined. Next, the diode-arrays themselves were evaluated. A number of breadboard devices were then assembled on mini optical benches with micro-positioners and tested. Diode arrays, and later, receiver arrays, were received from R1027 (Integrated Opto-Electronics for Multichannel and Coherent Systems).

A number of prototype demultiplexers based on a symmetrical tubular construction have been designed and fabricated (Fig. 12). They were assessed with particular respect to ease of alignment, ease of connection to the diode or receiver array, and environmental stability. The most promising configuration was then selected for further development. It was shown that the optical performance of the demultiplexer subsequently developed met the R1036 target system specification and had excellent environmental stability.

In conjunction with R1027, an early tubular design incorporating a 2-channel hybrid receiver, for operation at 155 Mbit/s, was supplied to the BBC for the interim test bed and for exhibitions.

In a further joint exercise with R1027, an early sample of a 4-channel, 622 Mbit/s integrated transimpedance receiver array has been incorporated in a tubular demultiplexer and its operation verified.

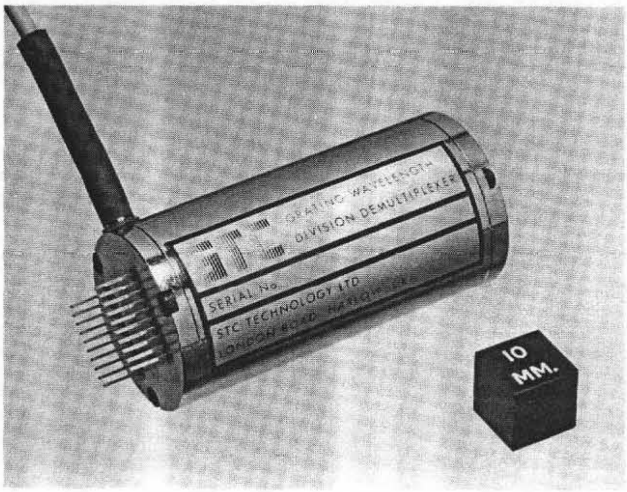

**Fig. 12.** A diode-coupled optical demultiplexer with side-entry input fibre

A feasibility study on the use of a diode-coupled demultiplexer for laser wavelength tracking has been completed. A wavelength tracking facility monitors the system laser wavelengths and corrects them, if necessary, for any wavelength drift.

In summary, it is concluded that the progress made, particularly in the packaging and interfacing of the demultiplexer bulk optics and the diode or receiver arrays shows that a demultiplexer with an integrated receiver array is a practical and attractive route for achieving considerable cost savings in high-density wavelength multiplexed systems.

### 4.6 Receivers

The chief activity of Thomson-CSF/LER within the framework of this Project has been in developing optical receivers and the high-bitrate electronics needed for clock regeneration and data recovery.

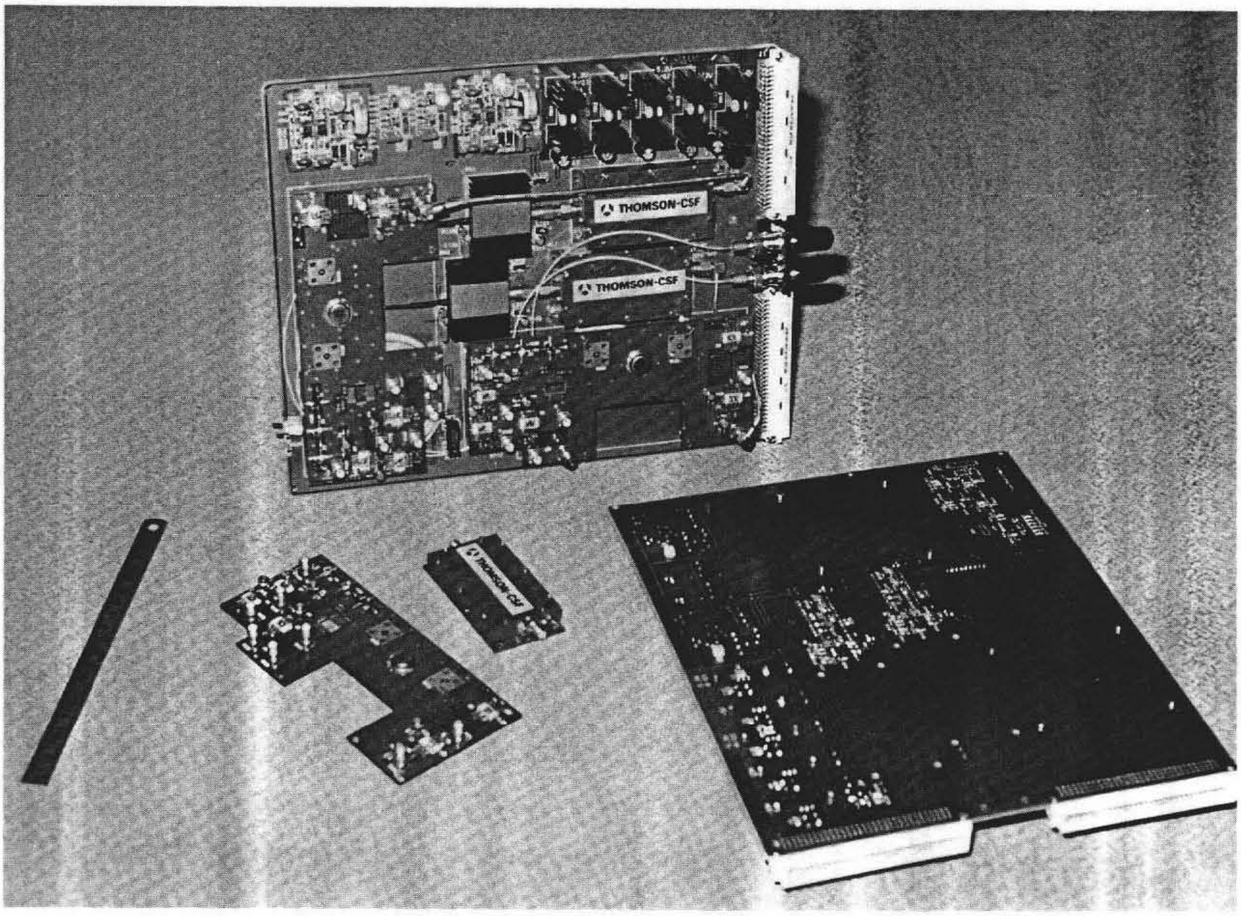

**Fig. 13.** Two-channel 2.5 Gbit/s optical receiver assembly

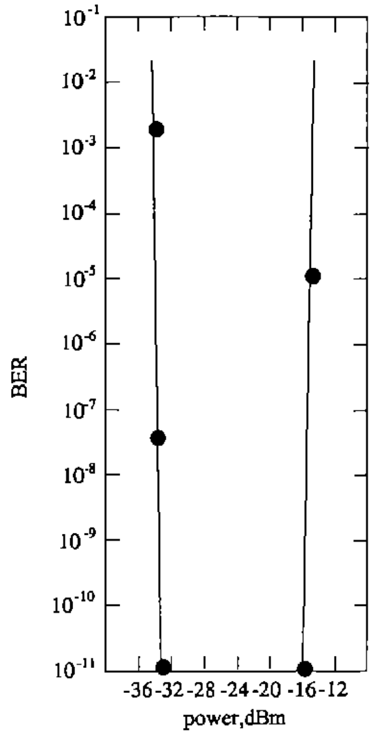

**Fig. 14.** Measured error rate of optical receiver

The main objectives were to design, evaluate and fabricate as many optical receivers and clock recovery modules as possible operating at the STM-16 level for inclusion in the Project test bed. An important activity was also carried out concerning an expandable ultra high-bitrate switching matrix.

A board containing two receiver channels has been designed (Fig. 13). Each channel includes:

- transimpedance hybrid circuit
- 150 V DC/DC converter for polarisation of the APD
- low noise broadband main amplifier
- clock recovery function

The main characteristics of the optical receiver are a low noise-threshold and a wide dynamic range; Fig. 14 illustrates these features. Twelve receiver channels have been delivered for inclusion in the final test bed.

A 2.5 GHz clock recovery circuit has been designed; this is required to regenerate data clock both in optical receivers and at the output of high-speed switching matrices. The circuit is based on a high-*Q* filter followed by a transition detector, as shown in Fig. 15. Transitions in the clock waveform occur at twice the rate of those in the 2.5 Gbit/s NRZ data, presenting one of the major design problems because of the demands on device speed.

## 4.7 Selector Electronics

Swindon Silicon Systems have also been involved in the design of the switch matrix ASICs, which operate at bit rates in excess of 2.5 Gbit/s. As with the multiplexer and demultiplexer, the process developed in the Esprit TIP-Base Project was used.

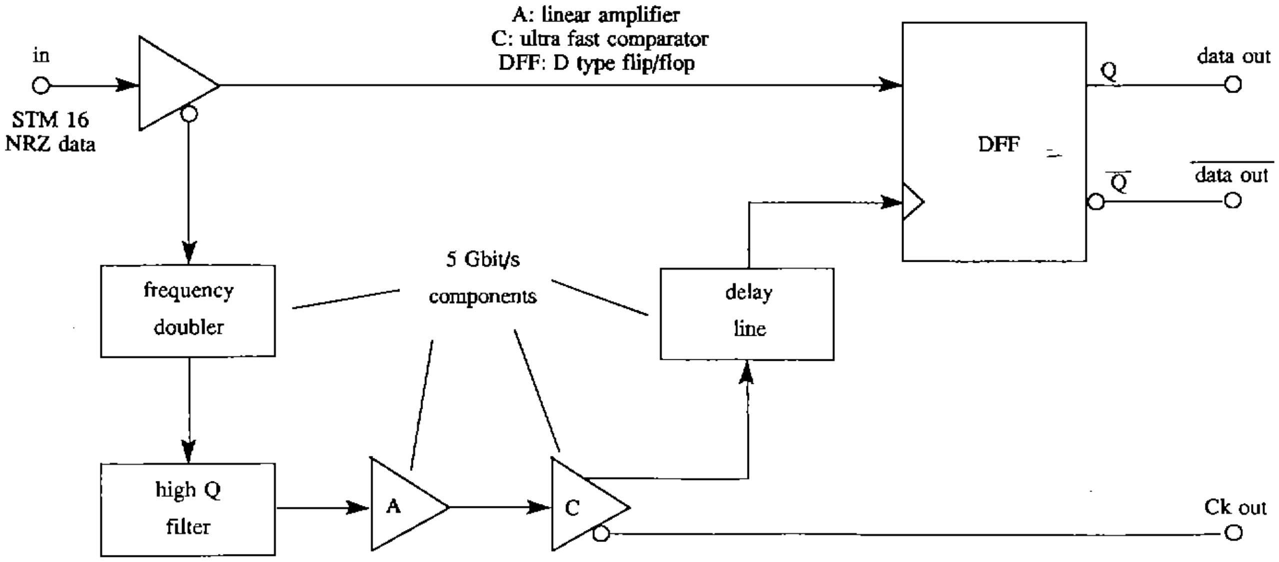

**Fig. 15.** Schematic of 2.5 GHz clock regenerator

The design goal for the switch matrix was to produce a non-blocking crosspoint switch to digitally cross-connect 2.5 Gbit/s serial bit streams, with minimum distortion and cross-talk between the data paths. An architecture was therefore chosen whereby the control switch matrix IC would communicate to the systems via a set of input and output buffer ICs which translated from industry-standard signal specifications to the signal levels employed on the switch matrix IC. The switch matrices were built in multi-chip sub-systems modules, and full differential logic employed in the design to minimise the signal degradation. Significant research into suitable package technologies was required due to the large number of very high bit-rate signals that interface with the devices. To optimise the performance it was necessary to create tightly controlled transmission lines up to the chip interface, as far as this was consistent with the requirement to use standard chip bonding techniques.

## 4.8 IBCN interface

The IBCN interface is responsible for the interworking of the WTDM customer premises network and a public broadband ISDN network; a block diagram is shown in Fig. 16. This interface is the gateway between the WTDM test bed and the rest of the B-UNI Demonstrator prepared by R1081 (in which the Prime Contractor of R1036 is a Partner to represent the Project).

An important characteristic of the WTDM network is that user data (such as video) and signalling data are carried in separate streams. User data is transported in VC-4 containers, while signalling data is carried outside the STM-1 payload. At the Broadband User Network Interface (BUNI), all information is multiplexed in the same 155.52 Mbit/s ATM-based interface. It was therefore necessary to integrate signalling and user data in the outgoing direction and to separate the signalling and user data in the incoming direction. This multiplexing and demultiplexing is performed by the Cell Insertion and Extraction Module (CIEM). A major part of the work for the IBCN interface has been the design and implementation of this module.

The CIEM has the task of extracting signalling cells from an incoming ATM stream, replacing them by idle cells, and in the other direction detecting idle cells and replacing them by signalling cells if needed. To fulfil these tasks, the incoming serial 155 Mbit/s signal is first converted to a parallel data stream. This requires clock recovery, CMI decoding

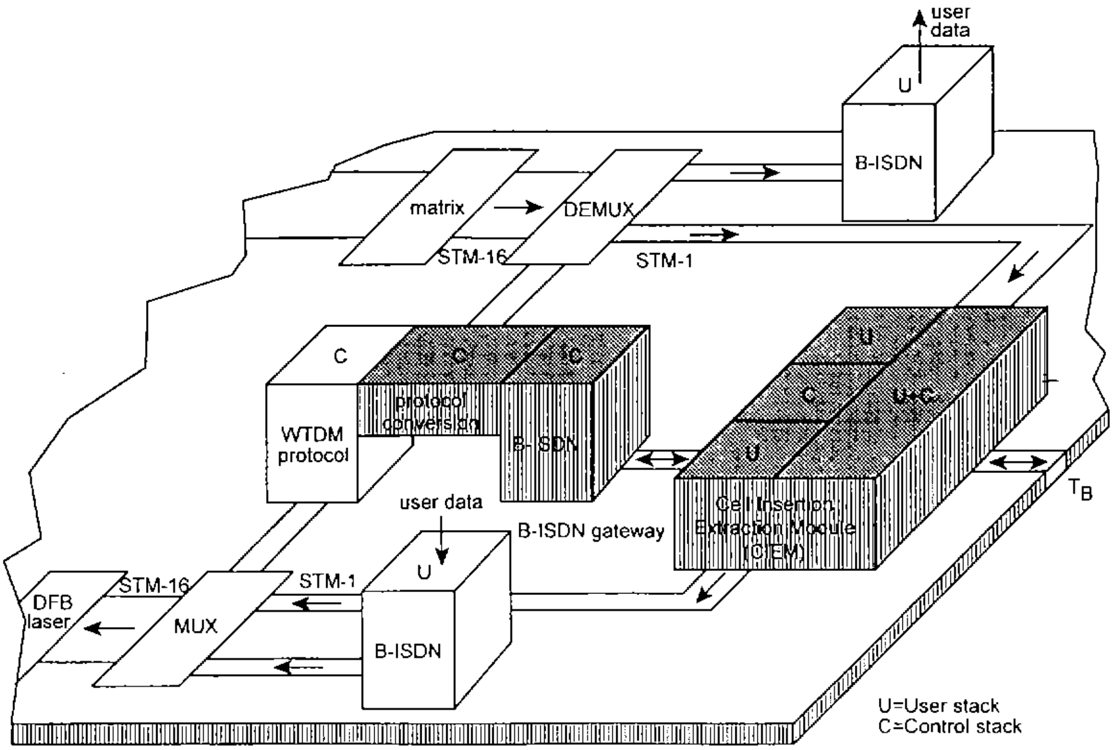

**Fig. 16.** Functional block diagram of the IBCN interface

and STM-1 frame synchronisation. The STM-1 payload of the STM-1 signal is localised, after which an ATM cell synchroniser searches for the individual ATM cells. The ATM cells are descrambled, and their VCIs are inspected. If needed, some ATM cells are replaced. Then the whole process is reversed, resulting in a proper 155 Mbit/s ATM stream again.

The protocols that are used internally within the WTDM network are based on N-ISDN protocols and are incompatible in several ways with the BUNI protocols. In order to make both systems co-operate, a protocol converter has been implemented. This converter contains two complete protocol implementations, one for the BUNI protocols and one for the internal WTDM protocols. The actual conversion takes place at the call control layer.

The implementation of the IBCN interface is expected to be finished around the end of the year. Since no testing facilities are available in this Project, the result cannot be fully tested. However, since the WTDM network will be a part of the BUNI Demonstrator network, the IBCN interface will be tested by R1081 as part of their acceptance testing in the first quarter of 1993. Results will appear in the R1081 deliverable RD/6/03 "BUNI Demonstrator and Tb Evaluation Report".

### 4.9 Control

The purpose of the control system is to control the operation of the switching components in the system and to provide a simple user interface by which the system can be operated. The switching functions in the WTDM network are distributed over the network: both wavelength selection and timeslot selection are performed at the destination side of a connection. It is the task of the control system to hide this distributed switching from the user and to pretend it is a single, centralised switching matrix. In addition to this, the control system also has the task of gathering information about any failing component and of presenting this information to be the user in a comprehensible way.

The following components are controlled:

- Electrical demultiplexers (time slot selection)
- Switching matrices (wavelength selection)

The following components need to be scanned periodically for information about their proper operation:

- Optical receivers (optical power low, electrical power low)
- Laser transmitters (optical power low)

In order to fulfil these tasks, each local routeing centre has been equipped with a control module that drives the local switching components and that scans the local alarm signals. The control module has been build around a MC68020 VME processor board. A medium speed parallel bus is used to interface the control module with these components. A simple interface board for this bus has been designed and implemented.

In order to distribute switching commands over the network and to report on all alarm conditions at an arbitrary location, a control network has been implemented that links all local routeing centres.

According to the initial design, the transport capacity for this control network was to be provided by the D1 and D2 octets in the section overhead of the STM-1 signals. For this purpose, signalling interfaces were designed and implemented to offer a capacity of 2 Mbit/s. At a later stage, this solution turned out to be impracticable since it would have required separate demultiplexers for the signalling links. By 'piggy-backing' the signalling information in STM-1 channels it is switched with the data. In a new design, this would have been solved in a different way.

For the proper operation of the signalling network, a set of signalling protocols have been designed and implemented. First of all, a datalink layer has been specified, based on CCITT recommendation Q.921 (N-ISDN datalink layer). This datalink layer takes care of error detection and correction, and flow control on each of the datalinks. On top of this datalink layer, the call control layer takes care of setting up and breaking video and audio connections. Initially, the call control layer was an adapted version of CCITT recommendation Q.931 (N-ISDN call control). In a later stage, it became clear that this protocol could not offer all the functionalities that are desirable in a broadcasting production environment, and hence a completely new call control layer was specified and implemented.

For the specification, implementation and testing of the required protocols, extensive use was made of the CCITT specification language SDL. Some experimental tools were used in the translation from specification to implementation. The experience obtained with this new methodology has shown that is very suitable for the development of protocols for broadband communication.

On top of the call control layer, a simple user interface has been implemented. This includes some easy-to-operate push button panels with illuminated buttons. These panels can show the existing connections, and connections can be made and broken by simple keystrokes. If required, an optional VDU can show more information, e.g. the status of the alarm signals.

### 4.10 Test bed

The Project assembled an interim test bed in the form of an exhibit suitable for demonstration at conferences and exhibitions. First shown at IBC '90, this exhibit demonstrates multiplexing of two optical wavelengths each carrying a PAL video signal at the STM-1 rate of 155 Mbit/s. For demonstration at ECOC '91, a third wavelength carrying a pseudo-random binary sequence (PRBS) at the STM-16 rate of 2.5 Gbit/s was added and the control system was integrated for selection of sources at destinations

The Exhibit has also been publicly demonstrated at the International Conference on Broadband Services and Networks (London, 1990), at an HDTV conference in London, at IBC '92 (Amsterdam) and on the EC stand at the exhibition Fantastiske Fremtid (Fantastic Future - Ålborg, Denmark). It has also travelled to the Technical Audit (Brussels), to Partners GEC Hirst Research (North Lon-

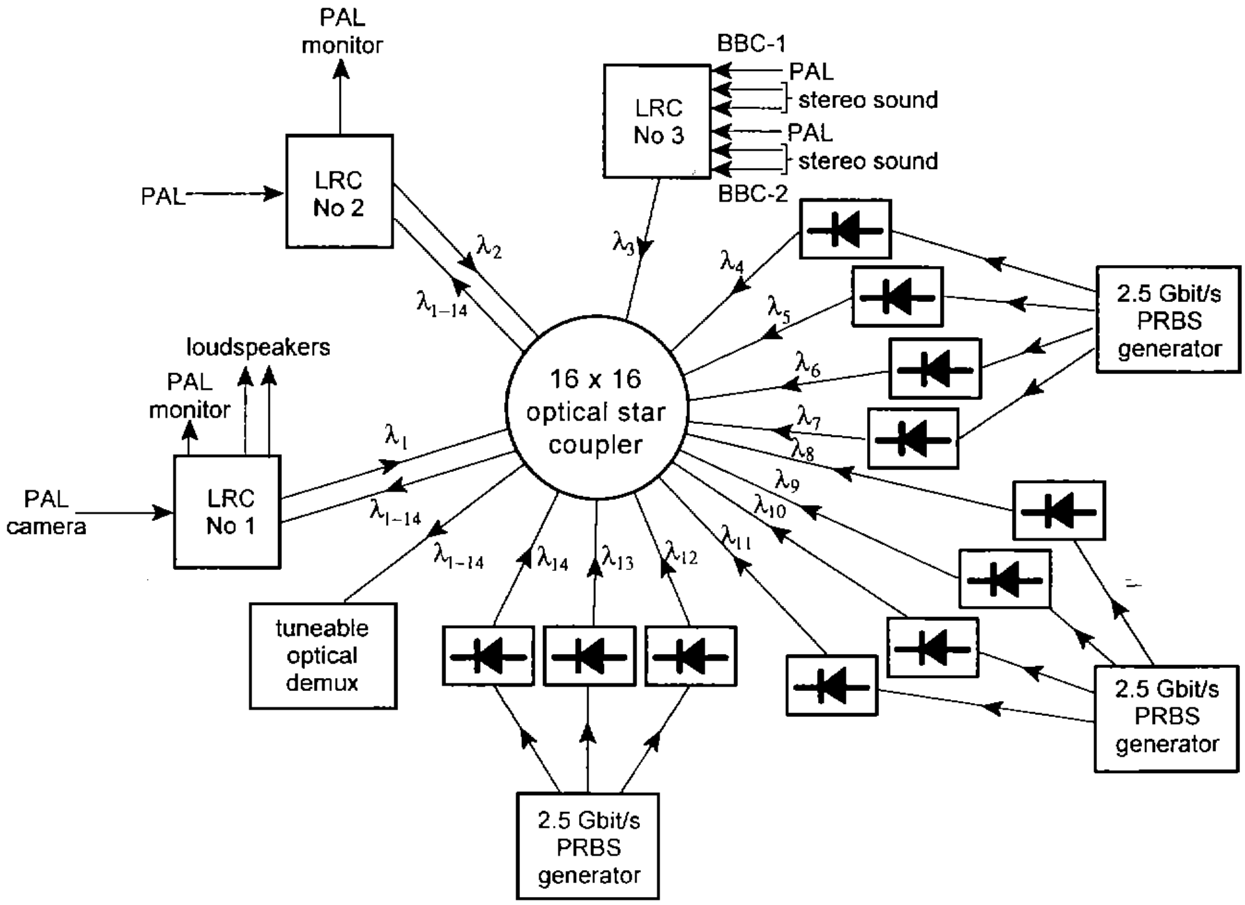

**Fig. 17.** Schematic of R1036 final test bed

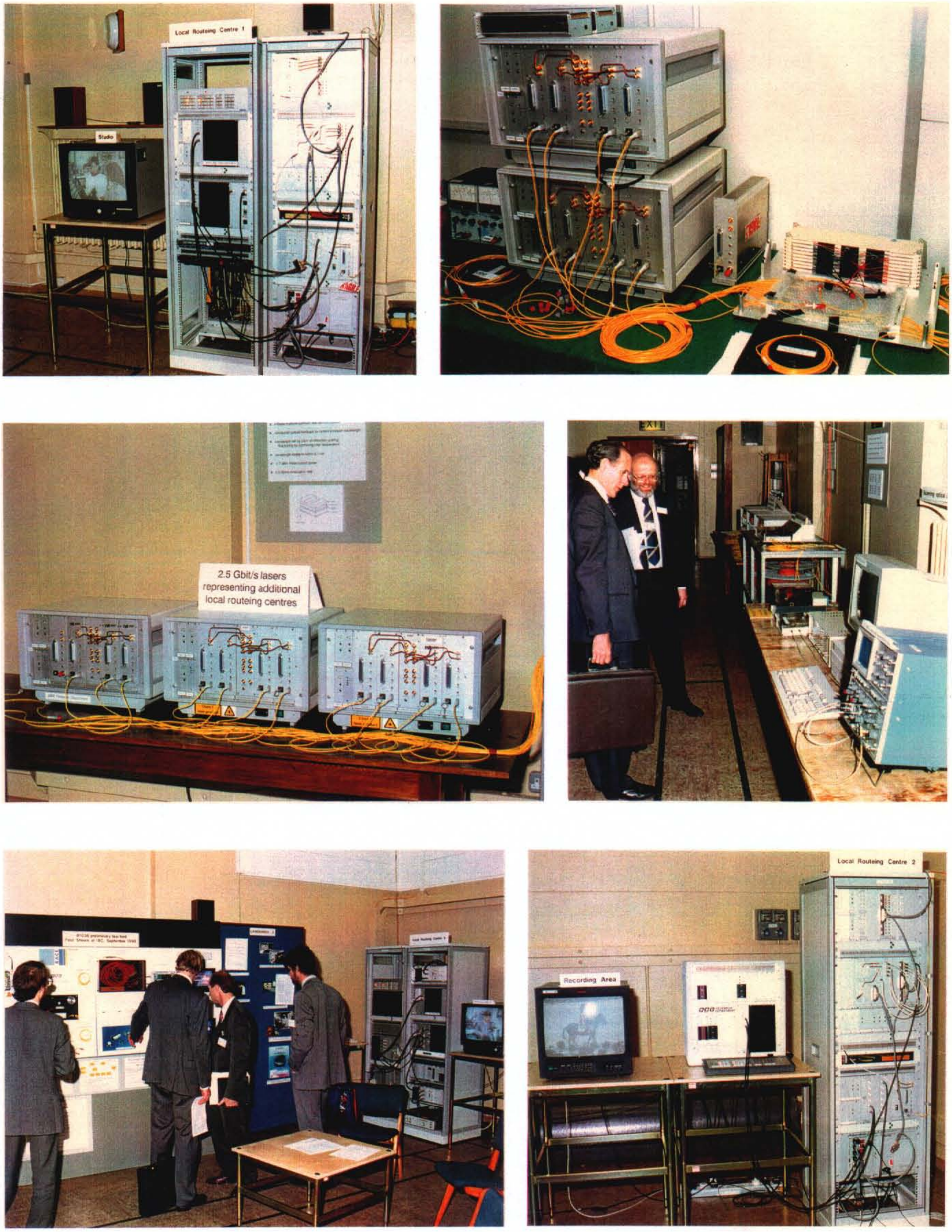

**Fig. 18.** Demonstration of the final test bed at BBC Research Department in November 1992

don) and NT Europe (South-West England), and to the BBC's Engineering Training Centre (West of England) and has been shown to many visitors at BBC Research Department.

In the meantime, the Project's final test bed has been completed (Fig. 17). It consists of fourteen laser transmitters at different wavelengths spaced by 4 nm of which four are modulated with 2.5 Gbit/s multiplexes including HDTV, video, and audio signals; the rest are modulated with 2.5 Gbit/s PRBSs. For this purpose several 2.5 Gbit/s PRBS generators have been built. The PRBS is generated in an 8-bit parallel form at 310 MHz and the eight bitstreams are multiplexed together to give the 2.5 Gbit/s PRBS. This parallel generation technique reduces power consumption by 40% and component cost by 60% compared with a serial implementation.

The equipment for the final test bed occupies five bays, each about 2 m tall, plus some smaller cases. Interfaces for HDTV, video, and audio signals are being provided by R1081; the rest of the equipment has been made by R1036 partners.

Initially, first samples of the MUX and DEMUX boards were used to try out the optical transmitters and receivers via a fibre-optic attenuator, and results indicate that the system power budget was realistic.

The final test bed was demonstrated to invited audiences including Partners, representatives of the UK Department of Trade and Industry, representatives of other RACE Projects, other broadcasters, and the Press.

After the completion of the R1036 demonstrations, most of the final test bed is being used in System II of the BUNI Demonstrator (R1081).

## 5 INPUT TO STANDARDS AND COMMON FUNCTIONAL SPECIFICATIONS

As R1036 is a Part 2 Systems Project, direct work on standards is not a primary aim. However, the Project has followed the work on Common Functional Specifications, with the aim of contributing wherever possible and has reported its work to other standardisation bodies. R1036 has contributed to the work of STG 3.3 (transmission) on wavelength planning for high-density WDM. In particular R1036 has contributed to CFS E334 (Optical CATV UNI for HDWDM transmission) and to a reply to a liaison statement from STG 2.3. In both cases contributions were based on experience gained from the hardware developed within the Project.

The work on the IBCN interface has identified a number of errors in the BUNI specification; these have been reported to R1081 and R1044.

The work of STG 5.5 on CPNs has also been monitored; contributions were made on the evolution of the broadband CPN and on technological aspects of broadband CPNs. However, very little of these contributions has appeared in CFSs.

Work from R1036 on wavelength stability will have a direct impact on R2001, which, it is hoped, will have some part to play in definition standards for WDM applications within SDH systems.

## 6 OVERALL IMPACT AND EXPLOITATION OF RESULTS

The Project has achieved world leadership in broadband optical network technology. Its demonstrations of optical networks using components made to an agreed specification by Partners in different companies in different European countries have validated the concept of collaborative research in Europe and have attracted great interest from USA and Japan. Because it incorporated a control system to select sources at destinations and to monitor the performance of the network, the final test bed was seen by potential users not only as a technology demonstrator but also as a convincing demonstration of a possible future product.

The Project has been invited to contribute to special issues of *Electronics & Communications Engineering Journal* (August 1992) and *Journal of Lightwave Technology* (to appear early 1993). Taken with the invited paper presented at ECOC '90 and the acceptance of contributions by the *IEEE Journal of Solid-State Circuits* and the Custom Integrated Circuits Conference in Boston USA, these invitations demonstrate the recognition of the Project's work by the technical community outside RACE.

The work of the Project will be continued towards exploitation by a RACE II Project, R2001, which aims at a pilot installation of an optical routeing network in an operational environment. The partners hope that the devices that have been developed as prototypes in R1036 and other RACE I Projects will emerge as products from R2001.

## 7 SELF ASSESSMENT

### 7.1 Assessment by Prime Contractor

The Project has now come to a successful conclusion. It has established the principles of close-spaced wavelength multiplexing and of network control; despite some problems with the electrical multiplexing, the final test bed demonstrated the multiplexing of broadband signals to the STM-16 rate of 2.5 Gbit/s. The work will be continued in R1081 (BUNI Demonstrator) to demonstrate HDTV transmission and to validate the IBCN interface. Thus all the elements of the original Project Plan will have been fulfilled.

These achievements would not have been possible without the ready co-operation of all the Partners as companies, and of all the engineers who represented them in the Project. The Project has indeed been fortunate in the expertise and breadth of understanding of the engineers who have worked on it.

The management of the Project has been based on a series of technical and coordination meetings — generally six or seven during each year. There has been an excellent continuity of representation, with occasional changes being preceded by an adequate handover period. All meetings have been well attended and there has been a high level of technical discussion in a friendly atmosphere, with difficulties being raised only with a genuine intention of contributing to their solution.

During the final year, when most of the business of R1036 has been progress reports rather than discussion of major technical issues, meetings have been held jointly with the continuation Project R2001 which has a number of common Partners; Partners involved only in R1036 have attended on one day only when business relating to R1036 and coordination matters relevant to both Projects have been discussed. This procedure has maintained interest in R1036 and has enabled a smooth transition between the two Projects.

### 7.2 Assessments by individual Partners

**Alcatel SESA**

Alcatel SESA has improved its position towards the application of the CCITT G.707, G.708 and G.709 recommendations experienced in the WTDM-BCPN R1036 Project.

**BNR Europe Limited**

The five year Project has been very successful. This is demonstrated by the award of a RACE II contract to implement the WTDM BCPN system developed. In addition, the interim test bed has been exhibited at many prestigious events, enhancing the visibility and reputation of WTDM systems, RACE in general and of course, the Project itself. The management team at the BBC has performed an excellent job in keeping the Project on course and on schedule.

**GEC-Marconi, Hirst Research**

The final year of this Project has culminated in a number of demonstrations of the advanced technology developed within R1036. This is a result of excellent collaboration between the partners and good Project management by the prime contractor over the past five years.

**Northern Telecom Europe Limited**

R1036 has provided an excellent base from which R2001 can develop optical components both for WDM intensive systems and for more general use in providing expansion capability for existing SDH systems.

**PTT Research**

Good progress has been made this year. Since this Project is reaching its end, deadlines are becoming tight and a lot of work had to be completed. This has asked much effort, flexibility and improvisation of all partners. Especially the prime contractor deserves a compliment for successfully managing this Project.

### Swindon Silicon Systems

During the final year the Project has proceeded to schedule with many of the components being assembled in the demonstrator. The collaboration between partners has been excellent, and Project review meetings have been carried out in a friendly and cooperative atmosphere.

This year has seen the results of the multiplexer and demultiplexer ICs, which with the much appreciated cooperation of SGS-Thomson TIP BASE Project has culminated in a set of working devices. This has significantly increased confidence in the high speed electronics, and will allow the Project to be successfully completed.

### Thomson-CSF/LER

This Project is now finishing and Thomson has been proud to collaborate to it. The important work concerning specifications which has been carried out during the two first years of the Project had led to a system easy to fit together as it has been shown in several exhibitions.

During all the Project all the work was carried out very efficiently in a very friendly and constructive atmosphere so all technical problems, even very severe, have been solved. Now we are looking forward to see this concept of WTDM implemented in a real environment such as an important broadcasting centre to fully demonstrate the flexibility of such a network.

### SGS-Thomson

The good results of the second iteration of the interleaver and deinterleaver ICs have confirmed the options taken in terms of process and architecture. A new shuffler-scrambler compatible with 8 bit GaAs Mux/Demux ICs has been successfully designed, without extra cost, as a backup solution.

## ANNEX 1: List of published papers

1. OLIPHANT, A., 1988. "Progress in the development of a digital optical routeing system for television studio centres". IBC 88, IEE Conference Publication No. 293, pp 90-94.

2. OLIPHANT, A. (Editor), 1989. "The first year's work of RACE Project 1036. WTDM Broadband Customer Premises Network". BBC Research Department Report No. 1989/6.

3. KIRKBY, P.A., BAKER, N., LEE, W.S., KANABAR, Y., WORTHINGTON, R., 1989 "Multichannel grating demultiplexer (MGD) receivers for high density wavelength multiplexed systems". IOOC, Tokyo, July 1989.

4. AULIA, A.N., VENEMANS, P.H.A. "A skeleton for the specification of OSI protocols in SDL". Fourth SDL Forum, Lisbon, October 1989.

5. ROBERTSON, A.J., CANNELL, G.J., WORTHINGTON, R. "Diode-coupled high-density wavelength demultiplexers". IEE Colloquium on optical connection and switching networks for communication and computing". 14 May 1990. IEE Colloquium Digest 1990/076.

6. AULIA, A.N., BLANKERS, P.F.C., MULDER, H., 1990. "Distributed control for a high-speed optical customer premises network". ISS 90, Stockholm, May 1990.

7. NOURSHARGH, N., CANNELL, G.J., WALTERS, J., LE ROUX, P., LAUDE, J.P., ZUBRZCKI, J.T. "Advanced optical components for high bit-rate WDM networks". EFOC/LAN 90, Munich, 27-29 June 1990.

8. CANNELL, G.J., ROBERTSON, A.J. "Practical realisation of a high-density diode-coupled wavelength demultiplexer." IEEE Journal on Selected Areas in Communication: Dense wavelength-division multiplexing techniques for high-capacity and multiple-access communication systems, August 1990.

9. MARSDEN, R.P., ALLEN, J.J., CANNELL, G.J., LAUDE J.P., MULDER, H. "A multi-gigabit/s optical business and communications system using wavelength and time division multiplexing techniques". ECOC 90, Amsterdam, 16-20 September 1990. (Invited paper)

10. OLIPHANT, A. "Routeing for the future". TELEVISION — Journal of the Royal Television Society, November 1990.

11. ROBERTSON, A.J., CANNELL, G.J., GEEAR, M., LEE, W.S. "Diode-coupled high-density demultiplexer for multi-wavelength optical systems". Conference on high-performance electronic packaging. The Welding Institute, London, 29-30 November 1990.

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